The radio occultation instrument GRAS on-board of Metop-A has been measuring occultations since its activation on 27 October 2006 with only a few interruptions. On average, more than 600 occultations are collected during a day. Within this work, we briefly describe the GRAS instrument and processing, and then focus on validation of the bending angles by comparing them to co-located ECMWF and COSMIC profiles. We focus on a core impact height range from 8 km to 40 km, which is not affected by orbit approximations or limitations of the applied geometrical optics processing. Found agreement is generally good, above 40 km GRAS shows lower noise than COSMIC.

INTRODUCTION

The Metop-A satellite is part of the EPS (EUMETSAT Polar System), and is EUMETSAT's first LEO (Low-Earth-Orbit) satellite. In total, there will be 3 Metop satellites, each with an expected life-time of 5 years. EPS is expected to provide data for at least 14 years (successive satellites will be flown with overlap times). All Metop satellites will fly in a sun-synchronous orbit, altitude about 820 km, equator crossing Local Solar Time at 9:30 in descending node. Each orbit of data (about 100 minutes) is down-linked over the Svalbard Archipelago at 78° N. For more information and a general introduction on EPS, please refer to Klaes et al. [2007].

One of the instruments on-board of Metop-A is GRAS (GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding), a radio occultation instrument specifically designed for this task. It observes setting and rising occultations from the GPS (Global Positioning System) satellite constellation. Within this work, we validate recent GRAS measurements with co-located ECMWF (European Centre for Medium Range Weather Forecasts) profiles as well as with co-located observations from the COSMIC (Constellation Observing System for Meteorology, Ionosphere & Climate) radio occultation constellation of six satellites.

GRAS INSTRUMENT, PROCESSING, AND DISSEMINATION

The GRAS radio occultation instrument is capable of tracking up to 8 GPS satellites on the zenith antenna, which is used for precise orbit determination. In addition, it has velocity and anti-velocity viewing antennas for occultation tracking, both are capable to track 2 occultations simultaneously. With the current GPS constellation of around 30 satellites, more than 600 occultations are tracked per day. GRAS is capable of tracking in closed-loop and in raw sampling mode (also called open-loop), where the former is at 50 Hz and the latter at 1000 Hz. Tracking is performed from the lowest part of the atmosphere up to about 80 km. Please refer to Luntama et al. [2008] for more details on the instrument.

The GRAS PPF (Product Processing Facility) processes the data up to so-called level 1b, where the main products are bending angle over impact parameter, geo-location, time, and type of measurement. The first processing step determines the Metop orbit, which is operating on 60 s of zenith data.
with the SRIF (Square-Root Information Filter). Additionally, precise GPS orbits and clocks are required, they are provided by the GSN (Ground Support Network) \cite{Zandbergen2006}. The obtained Metop orbit is generally within the requirements of 0.1 mm/s in velocity and 1 ns in clock error at 1 Hz; for more information please refer to Martinez et al. \cite{Martinez2007}; Montenbruck et al. \cite{Montenbruck2008}; Andres et al. \cite{Andres2008}.

The bending angle processing of the currently operational PPF (version 2.11) uses only closed-loop data where both GPS frequencies are tracked, no raw sampling data is processed operationally. Bending angles are not optimized with a climatology, they are based on zero differencing and the geometrical optics assumption. Thus data below about 8 km to 10 km impact height is degraded, in particular at lower latitudes. At altitudes above about 40 km, approximations in occultation antenna position with respect to the orbit affect the data quality. These approximations still allow processing within the initial requirements for bending angles of an absolute accuracy of 1 µrad or 1 % (which ever is larger).

Dissemination of GRAS level 1b is performed through EUMETCast, providing the full data set in the EUMETSAT format \cite{Luntama2005}, and in BUFR format (restricted to the core products needed for assimilation, for more information please refer to Offiler \cite{Offiler2007}). A thinned version of the core products is also disseminated in BUFR on GTS (Global Telecommunication System) and EUMETCast, where profiles are currently thinned to a predefined set of 247 heights. All products are available latest within 2 h 15 min from observation time.

Processing from bending angles to level 2 is performed at the GRAS SAF (Satellite Application Facility). Level 2 products are e.g. refractivity, temperature, and water vapor profiles, available within 3 h from sensing time. Please refer to the GRAS SAF website for more information and availability [GRAS SAF].

In addition, all Metop data is available in offline mode from the U-MARF (Unified Meteorological Archive and Retrieval Facility) at EUMETSAT. Please refer to the EUMETSAT home page for further information [EUMETSAT].

DATA

The GRAS data for this study has been obtained from the operationally running PPF node on the EUMETSAT ground segment, version 2.11. It covers more than 40 days from September and October 2008. In total, there are almost 27,000 occultations, about 600 are removed because they either provide no valid bending angles (e.g. because L2 tracking was not achieved), or they cover less than a 20 km impact height interval. The remaining occultations provide more than 620 occultations on average per day. Within the investigated period, dissemination of data was stopped for two days because the ground processing was affected by an incorrect setup. No degradation of the overall statistics was observed when including this data, thus these occultations have entered the statistics and are also available from the U-MARF.

The COSMIC files are obtained offline from the CDAAC (COSMIC Data Analysis and Archive Center, Boulder, USA) archive \cite{Kuo2004}, where we use archived netCDF data from the Near-Real-Time stream. In total, there are more than 75,000 occultations, providing on average almost 1800 occultations per day (or about 300 occultations per day and satellite). However, this number varies between a minimum of less than 1000 occultations to a maximum of more than 2500.

The ECMWF co-located profiles are drawn from 12 h forecast fields, available at EUMETSAT at times 00 UT and 12 UT, with a resolution of 0.5 Degrees, on 91 vertical hybrid levels. They are forward modeled to bending angles using the freely available ROPP (Radio Occultation Processing Package) developed at the GRAS SAF \cite{Offiler2008}.

All profiles are pre-processed to be available on 247 impact height levels, where impact heights are calculated from impact altitudes minus the local radius of curvature. The ECMWF profiles are up-sampled from the standard 91 model levels, the radio occultation data is thinned using a simple linear
interpolation in log bending angle space provided by the ROPP tool.

RESULTS

Figure 1 shows so-called \((O - B)/B\) statistics, where \(O\) is the GRAS bending angle measurement, and \(B\) the forward propagated ECMWF background. These statistics are evaluated at each impact height level, using robust statistics. The robust statistic is an effective tool to deweight outliers from a noisy distribution, it returns the standard deviation and percentage of data points falling into the \(\pm 2\) sigma interval. This would be 95\% for an ideal Gaussian distribution. For the PPF 2.11 data, about 90\% fall into the \(\pm 2\) sigma interval, thus an additional 5\% of the data has been deweight by the robust statistics. (Performing the same kind of robust statistics for the COSMIC satellites shows the much more strict quality control applied; about 94\% fall into the \(\pm 2\) sigma interval.)

The bias plot shows generally very good agreement for the core altitude range considered here, although the GRAS processing returns larger bending angles starting at about 35 km when compared to ECMWF fields. Deviations seen between 35 km and 40 km are also observed at ECMWF, thus are likely caused by other assimilated instruments at ECMWF (S. Healy, ECMWF, personal communication, 2008). Similar features can also be seen when comparing against fields from the UK Met Office. Both centers are currently testing lower radio occultation error estimates at higher altitudes in their assimilation setup to get further improvements from this type of observations.

Above 40 km, larger biases against co-located ECMWF profiles show up that are caused by the above mentioned occultation antenna position approximation with respect to the Metop orbit. Standard deviations clearly show the tropopause region, in particular at low latitudes. Here, gravity waves that are not fully represented in the ECMWF model are likely causing this observed increase.

Figure 2 shows robust bias and standard deviation against ECMWF forecast data calculated for GRAS and each of the six individual COSMIC satellite for altitudes above 10 km. The bias plot shows very similar results for the seven instruments up to about 35 km, although around 20 km to 30 km, GRAS shows a slightly lower value than any COSMIC data. This might be the impact of a particular processing setup on the observation, also called structural uncertainty. It is also found when processing the same satellite with different processing software, as e.g. described in von Engeln [2006]. Above 40 km, the already mentioned impact of the occultation antenna position approximation is visible in GRAS data.

The standard deviation plot shows very similar results between 10 km and 41 km for all instruments. Above, GRAS shows lower noise values than COSMIC. Between about 15 km and 35 km GRAS shows slightly larger standard deviations. This is likely caused as well by the data processing, indicating that the GRAS processing uses less smoothing. The GRAS instrument is also providing a much more robust number of occultations on average per day, while the COSMIC satellites show a large variation from a minimum of 177 to a maximum of 440.

Co-located occultations between GRAS and COSMIC have been identified in the 2 data sets. A match is assumed if the occultations are within \(\leq 3\) hours and \(\leq 300\) km. The number of found matches is mainly affected by the available COSMIC profiles, on average around 190 are found per day. Not all matches are unique, e.g. on average about 33 GRAS profiles per day are matched with more than one COSMIC one.

Figure 3 shows the robust bias and standard deviation obtained with the matched data set. The bias agreement is very good for the core altitude range, the deviations seen around 35 km to 40 km against ECMWF (Figure 1) are not present here, hence providing further evidence that this feature is introduced by the ECMWF fields.

The standard deviation plot shows increases around the tropopause for the different latitude bands. This also shows up in refractivity comparisons of GRAS and COSMIC at the UK Met Office (M. Rennie, UK Met Office, personal communication, 2008). A reduction in the standard deviation increase near the tropopause level is observed when moving to closer matches.
**Figure 1:** Operational GRAS PPF bending angles compared to co-located ECMWF profiles. Data from Sep and Oct 2008, PPF version 2.11. Robust bias (right), standard deviation (left) over impact height for 3 latitude bands separated in 30° steps. Grey shaded areas indicate regions affected by orbit (top) or by multi-path (bottom).

**Figure 2:** Robust bias and standard deviation for GRAS and COSMIC satellites. Number in brackets is average occultations per day. Period as in Figure 1.
Figure 3: Operational GRAS PPF bending angles compared to co-located COSMIC profiles. Otherwise as Figure 1.

NEXT STEPS

For the near time future (likely end of October 2008), we anticipate the following updates to the GRAS PPF: (1) better modeling of the antenna position in the occultation processing; (2) improved quality control, covering degraded orbit and degraded level 1b processing.

The first issue leads to the observed bias in bending angles at altitudes $> 40$ km. Although formally the currently obtained bending angles are still within requirements, the processing to refractivity leads to a bias observed at much lower altitudes. Improved occultation antenna position modeling is expected to resolve this issue. The second issue will allow better selection of which data to assimilate at Numerical Weather Prediction centers. Quality control at the moment is based on a simple range check, more sophisticated methods such as the calculation of a cost function with respect to a climatological profile are being implemented to identify severe outliers. In addition, degraded orbit quality will also be identified in this PPF updates. Such degraded orbit quality could for example arise from a reinitialization of the SRIF orbit propagator.

The longer term development will focus on the upgrade of the PPF to deal with multi-path regions by wave optics calculation (expected in 2009), and to improve quality control further through the use of variational assimilation [Marquardt et al., 2005]. Additionally, improved orbit processing to derive climate products from GRAS observations in offline mode are planned. Here, EUMETSAT will continue to provide level 1b data, while further processing is performed at the GRAS SAF.

CONCLUSION

GRAS bending angle data is disseminated to world wide users since early 2008, and the processing
achieved operational status in April 2008. Obtained bending angles agree very well with co-located ECMWF forward modeled data and also with COSMIC co-located profiles within an altitude range of 8 km to 40 km. GRAS operations is much more stable than the COSMIC one, providing more than 600 occultations per day. Although a bias is currently found in GRAS data above 40 km, caused by an approximation to the occultation antenna position, standard deviations already show that GRAS has lower noise in this range than COSMIC.

The current processing does not include a wave optics algorithm to deal with multi-path regions, hence the current data validation restriction at 8 km altitude. The observed bias above 40 km is expected to be resolved with the next PPF update to version 2.12 (currently scheduled for end of October 2008). Updates of the processor to deal with wave optics are expected in 2009.

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